Wave-driven equatorial annual oscillation induced and modulated by the solar cycle

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[1] Our 3-D model for the solar cycle (SC) effect on the QBO (H. G. Mayr et al., The QBO as potential amplifier of solar cycle influence, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Mayr et al., submitted manuscript, 2005) produces a hemispherically symmetric 12-month Annual Oscillation (AO) in the zonal winds, which is largely confined to low latitudes. This Equatorial Annual Oscillation (EAO) is generated through nonlinear interaction between the dominant anti-symmetric AO and the anti-symmetric component of the SC response. Due to wave-mean-flow interaction from small-scale gravity waves (GW), the SC-modulated EAO is amplified and propagates down through the stratosphere as does the QBO. The amplitude of the EAO is relatively small, but its SC modulation is large and is in phase with that of the QBO. Although the EAO is concentrated at low latitudes, prominent signatures appear in the polar regions where the SC produces measurable temperature variations. At lower altitudes, the GW-driven downward propagation of the EAO affects the phase of the annual cycle and causes the SC effect to be different in the two hemispheres.
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1. Introduction

[2] The equatorial oscillations of the zonal circulation in the middle atmosphere, the Quasi-biennial Oscillation (QBO) and Semi-annual Oscillation (SAO), have in common – besides being confined to low latitudes – that they are driven by waves. *Lindzen and Holton* [1968] demonstrated that the QBO (periods of 22 to 34 months) can be generated with planetary waves, and their theory was confirmed [e.g., *Holton and Lindzen*, 1972; *Plumb*, 1977] and extended to the SAO [e.g., *Dunkerton*, 1979; *Hamilton*, 1986]. Modeling studies with observed planetary waves revealed that small-scale gravity waves (GW) appear to be more important [e.g., *Hitchman and Leovy*, 1988]. *Takahashi* [1999] first succeeded in simulating the QBO with resolved GWs. But these waves generally need to be parameterized for global-scale models and in particular for long-term simulations. Employing Hines' GW parameterization, our model was among the first to simulate the QBO and SAO in the middle atmosphere [e.g., *Mengel et al.*, 1995; *Mayr et al.*, 1997].

[3] *Salby and Callaghan* [2000] showed that the QBO in the lower stratosphere appears to be strongly affected by the solar cycle (SC). They analyzed more than 40 years of zonal wind measurements at 20 km and found distinct features in the power spectrum, which revealed a 29-month QBO modulated by the 11-year cycle and its second 5.5-year harmonic. Band pass filtering of the spectrum produced a SC-correlated variation in the zonal wind power from 150 to 400 (m^2/s^2) or winds from 12 to 20 m/s.

[4] This analysis has been the impetus for a 3-D study with our model, in which we simulated the QBO under the influence of the SC (Mayr et al., submitted manuscript, 2005). The model generates in the lower stratosphere a relatively large modulation of the QBO, which appears to come from the SC and qualitatively agrees with the observations.

[5] There is observational evidence that the seasonal cycle influences the QBO [e.g., *Dunkerton and Delisi*, 1997], and this could also be a pathway for the SC influence. In the present paper we report that our model produces an equatorial annual (12 month) oscillation, which is induced and modulated by the SC and is the pacemaker for the QBO.

2. Numerical Spectral Model (NSM)

[6] The 3-D version of the NSM discussed is identical to that of Mayr et al. (submitted manuscript, 2005). With a SC period of 10 years, the amplitude of relative variation in solar radiation varies exponentially with height: 0.2% at the surface, 2% at 50 km, 20% at 100 km and above. For the zonal mean, the NSM is energized by absorption of EUV and UV radiation in the mesosphere and stratosphere [*Strobel*, 1978]. A time-independent tropospheric heat source reproduces qualitatively the observed zonal jets and temperature variations near the tropopause. The Newtonian cooling parameterization of *Zhu* [1989] is applied, but it is modified to keep the radiative relaxation rate constant below 20 km. Solar tides are generated by the heating rates for the troposphere and stratosphere [*Forbes and Garrett*, 1978].

[7] The NSM incorporates the Doppler Spread Parameterization (DSP) for GWs developed by *Hines* [1997a, 1997b]. The DSP introduces a spectrum of waves that interact to produce Doppler spreading, which affects the wave interactions with the flow. Due to enhanced advection in the tropics, a tropospheric GW source is adopted that peaks at the equator and is assumed to be independent of season. With the upper boundary at 130 km, a short vertical step size of about 0.5 km is employed to resolve the GW

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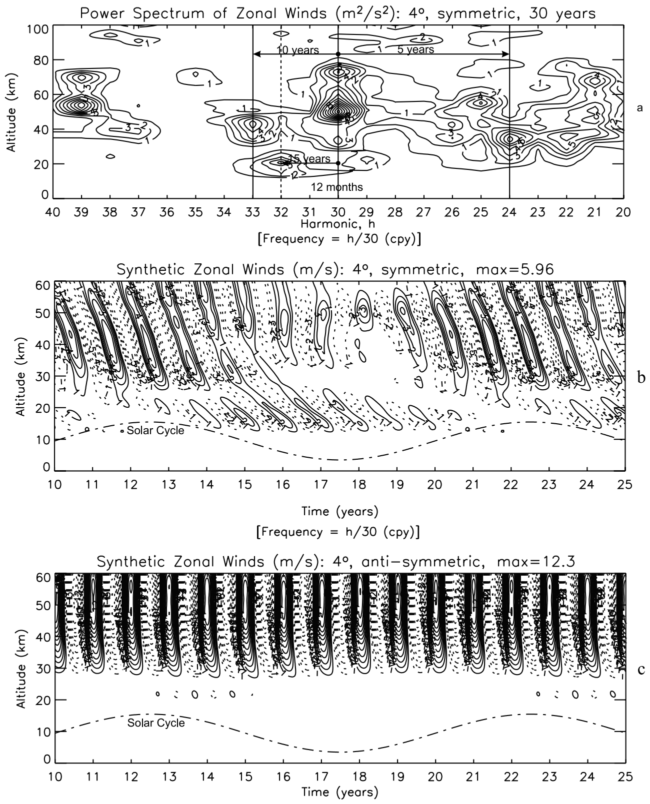

Figure 1. (a) Power spectrum at 4° latitude for the (hemispherically) symmetric component of the mean zonal winds, obtained from the 3-D model with solar cycle (SC) covering 30 years. The spectrum is presented in terms of discrete Fourier harmonics, h, which are related to the frequency ν = h/30 (cpy) in units of cycles per year. The Annual Oscillation (AO) with a period of 12 months occurs at h = 30, and the SC signatures associated with the periods of 10 and 5 years occur respectively at h = 33 (i.e., 30 + 3) and at 24 (30 − 6). Syntheses of the harmonics h = 27, 30, 33 describe the SC modulation of the AO for the (b) symmetric and (c) anti-symmetric components. Although the anti-symmetric AO is much larger at 60 km (Figure 1c), the weaker symmetric mode (Figure 1b) carries the SC signature to lower altitudes due to gravity wave (GW) drag.

interactions with the flow. The NSM is truncated at the meridional and zonal wave numbers l = 12 and m = 4, respectively.

3. 3-D Model Results

[8] Mayr et al. (submitted manuscript, 2005, Figure 1) present the computed zonal winds at 4° latitude to show that the model reproduces the essential features of the QBO and SAO. For both solutions with or without SC, the average QBO period is 22.5 months, which is near the lower limit of the observed range.

[9] We discuss 40-year model runs. Ignoring the first 10 years to allow for spin-up, the remaining 30 years are analyzed to reveal the Annual Oscillation (AO). In Figure 1, we present the results at 4° latitude for the solution with SC forcing. The power spectrum is shown in (a) for the (hemispherically) symmetric zonal wind field, with the 12-month AO identified at the harmonic h = 30. Associated with this spectral feature of the AO are the signatures of the 10-year SC at h = 33 (30 + 3) and its second 5-year harmonic at h = 24 (30 − 6). These side lobes describe amplitude modulations produced by nonlinear processes that essentially multiply the AO with the SC signatures. With abbreviated complex notation, the product between AO, $A\exp[i\omega_a t]$, and 10-year SC oscillation, $B\exp[i\omega_b t]$, thus generates $C_1\exp[i(\omega_a - \omega_b)t]$ and $C_2\exp[i(\omega_a + \omega_b)t]$ – which respectively have the frequencies corresponding to the harmonics h = 27 and 33 in Figure 1a. (The 15-year side lobe is discussed later.)

[10] The AO presented in Figure 1a is anomalous in that it is symmetric, in contrast to the regular and dominant AO that is (hemispherically) anti-symmetric. An important consequence of this property is shown with the syntheses of the spectral features h = 30 and (30 ± 3), which are presented in Figure 1 for the symmetric (b) and anti-symmetric (c) AO components. Although the amplitude of the regular AO (c) is much larger at 60 km, the weaker symmetric AO (b) extends to lower altitudes. Under the influence of wave-mean-flow interaction, the oscillation slowly propagates down like the QBO. The symmetric AO (b) is strongly modulated by the SC, whose phase is shown with dashed line. The amplitude of the AO peaks close to the maximum of SC forcing and, significantly, it is in phase with the maximum in the amplitude modulation of the QBO shown by Mayr et al. (submitted manuscript, 2005, Figure 3a). This SC-modulated symmetric AO is apparently generated by nonlinear coupling between the anti-symmetric component of the SC response and the dominant anti-symmetric AO.

[11] The anomalous symmetric mode of the AO is confined to low latitudes, as is shown with Figure 2a where we present at 40 km a synthesis of the same spectral harmonics employed in Figures 1b and 1c. The symmetric AO peaks at the equator, virtually disappearing at latitudes greater than 20°, and is therefore referred to as Equatorial Annual Oscillation (EAO). In contrast, the regular anti-symmetric AO in Figure 2b vanishes at the equator and increases towards mid latitudes. When the two AO components are combined in Figure 2c, the resulting SC modulation reveals an asymmetry between the two hemispheres. The SC modulated AO amplitude is larger in the southern hemisphere around the years 12 and 13 at SC maximum, but it is somewhat larger in the northern hemisphere during the minimum.

[12] For comparison, we present in Figure 3 the results for the symmetric AO generated without SC forcing. In this case, there is no SC signature in the spectrum (a). Instead a prominent 15-year modulation is evident that is also apparent in Figure 1a. As predicted [*Mayr et al.*, 2003], GW node filtering can generate a 15-year beat period through the interaction between the anti-symmetric AO and the 22.5-month QBO of the present model. This 15-year oscillation is then anti-symmetric and interacts with the anti-symmetric AO to produce the symmetric AO. Instead of the 10-year SC in Figure 1, an internally generated beat period generates the EAO in Figure 3. The oscillation is then amplified by the GWs and propagates down, which is shown in Figure 3b.

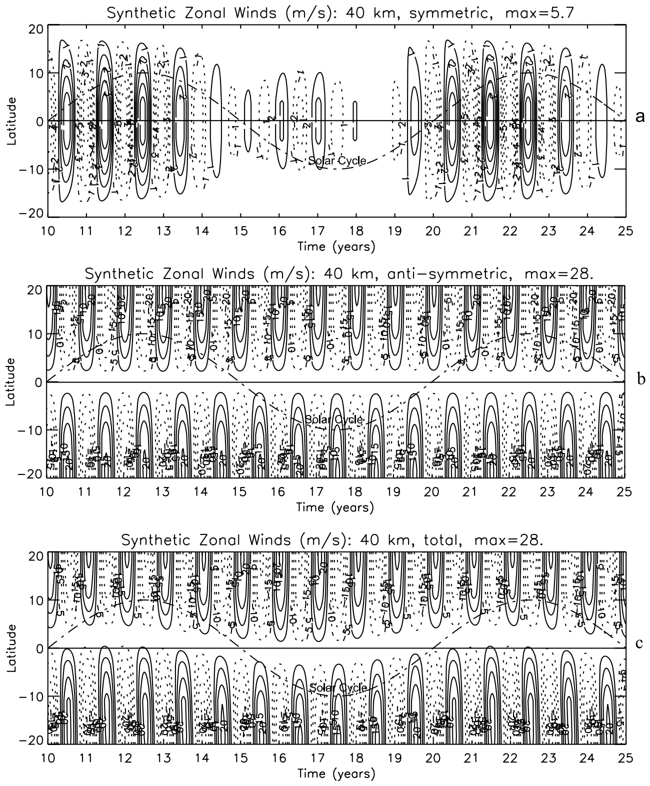

Figure 2. Syntheses of the spectral features at 40 km describe the 10-year SC modulations of the (a) symmetric AO, (b) anti-symmetric AO, and (c) total (symmetric and anti-symmetric) AO. The symmetric AO (Figure 2a) is confined to equatorial latitudes, while the anti-symmetric AO (Figure 2b) increases towards mid latitudes. In the total AO (Figure 2c), the SC signatures are produced by the symmetric component primarily.

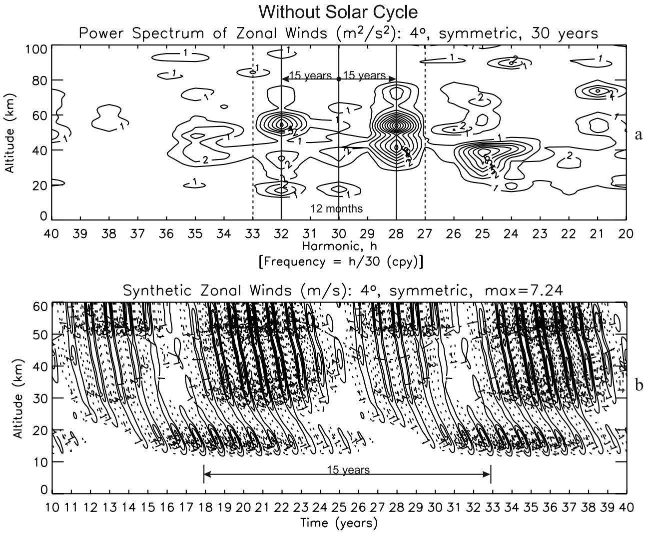

Figure 3. (a) For comparison with Figure 1a, the power spectrum is shown from the solution without SC. Instead of the SC signatures, 15-year spectral features are evident. (b) Synthesis of h = 28, 30, 32 produces the corresponding symmetric equatorial oscillation that propagates down under the influence of GW drag.

[13] As is the case for the SC modulation of the QBO, the EAO produces temperature variations near the poles. This is shown in Figure 4a, where we present the spectrum for the symmetric temperature perturbations at 84° latitude. The 10-year and 5-year side lobes related to the SC are pronounced. A synthesis of the harmonics h = 27, 30, 33 generates the SC modulation of the AO shown in Figure 4b. The symmetric AO appears to propagate down from the upper stratosphere to produce a SC modulation of about 1 K in the temperature near the tropopause.

[14] The global character of the symmetric AO is evident in Figure 5, where the latitudinal variations of the synthesized temperatures are presented for the harmonics h = 27, 30, 33. In panels (a) and (b), the symmetric AO is shown for the northern hemisphere at 60 and 15 km respectively. At both altitudes, the temperature variations are larger at the pole, but the differences relative to the equator are still larger at 15 km. The phase progression suggests that the AO propagates from the equator towards the pole. This is consistent with our assertion that the symmetric mode originates at equatorial latitudes where most of the energy resides and further justifies the label Equatorial Annual Oscillation (EAO).

[15] As seen from Figure 2c, a remarkable feature of this EAO is that it introduces a hemispherical asymmetry into the SC response. This is shown again in Figure 5c, where we present at 15 km for the northern and southern polar regions the synthesized temperature variations combining the symmetric and anti-symmetric AOs. In the northern and southern hemispheres, the AO amplitudes peak respectively before and after the SC maximum.

4. Summary and Conclusions

[16] We applied spectral analysis to describe the properties of the annual variations computed in a 3-D modeling study that describes the SC influence on the QBO (Mayr et al., submitted manuscript, 2005). The model produces a hemispherically symmetric 12-month annual oscillation

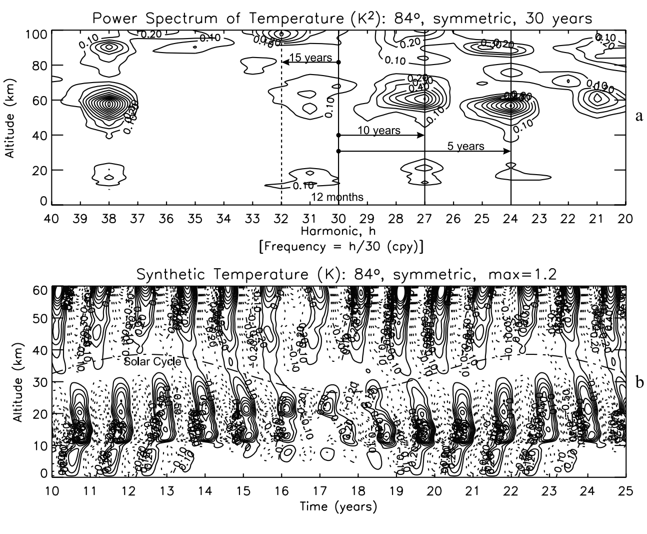

Figure 4. Similar to Figure 1 but for the temperature perturbations at 84° latitude. (a) The spectrum is shown, and (b) the synthesis describes the SC modulation.

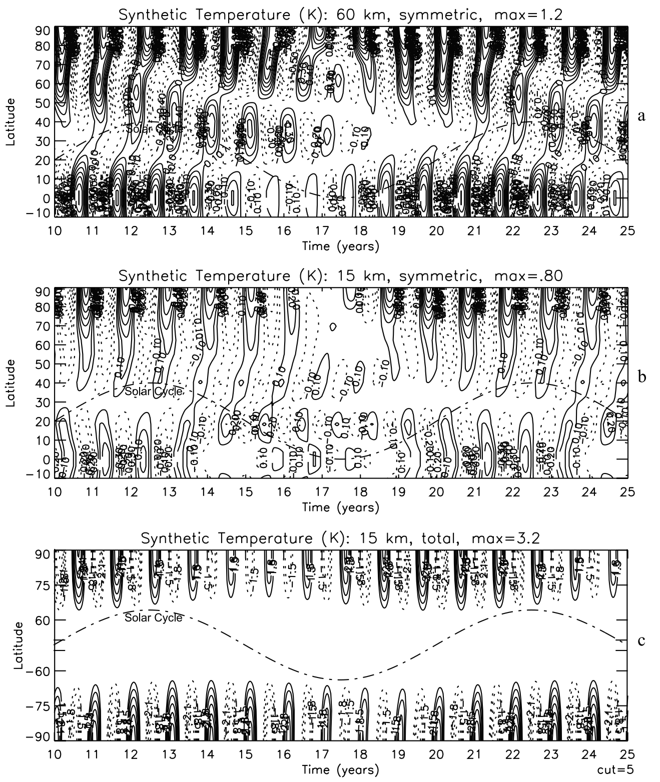

Figure 5. Latitudinal variation of synthesized temperature. (a) and (b) The symmetric SC modulations of the AO are shown respectively at 60 and 15 km. (c) With the lowest five contours suppressed, the total (symmetric and anti-symmetric) variations are presented for 15 km at polar latitudes to reveal the hemispheric differences.

(AO) in the zonal winds, which is confined to latitudes around the equator and is strongly modulated by the SC. This Equatorial Annual Oscillation (EAO) is apparently produced by the nonlinear interaction between the dominant anti-symmetric AO and the anti-symmetric component of the SC response. The symmetric AO is amplified in the equatorial region by tapping the momentum from the upward propagating GWs. Like the QBO, the EAO propagates down through the stratosphere and transfers the SC signature to lower altitudes. As shown in Figure 1b, the amplitude of the EAO is small, <10 m/s, but its contribution to the SC effect is significant in light of the small variations of solar radiation absorbed in the lower stratosphere.

[17] Although the energy of the EAO is concentrated around the equator, prominent signatures appear at high latitudes where the SC produces measurable variations in the temperature near the tropopause (Figures 4 and 5). As is the case for the QBO, the energy of the EAO is redistributed by the meridional circulation and planetary waves to be partially focused around the poles.

[18] The GW-driven downward propagation of the EAO affects the phase of the annual cycle at lower altitudes and causes the SC effect to be different in the two hemispheres. As shown with Figure 2c, the strongest and weakest amplitudes in the SC modulation occur at different times in the northern and southern hemispheres.

[19] An important feature of the EAO is that its SC modulation at equatorial latitudes is in phase with that of the QBO. This is apparent from a comparison between Figure 1b of the present paper and Figure 3a of Mayr et al. (submitted manuscript, 2005). The EAO is apparently the pacemaker for the SC modulation of the QBO.

[20] As Figure 3 illustrates, long-term variations can also be produced by the QBO interacting with the seasonal cycles. In principle, these could mask or mimic the SC signature and complicate the interpretation. This is probably not a serious concern for the SC modulations of the EAO and QBO in the present study. The generated periodicity is 15 years, far removed from that of the SC.

[21] To our knowledge, a SC-modulated symmetric annual oscillation has not been reported in the literature. We believe however that the oscillation pattern we describe could be involved in the so-called Arctic Oscillation, which represents a mode of variability that appears to propagate down from the stratosphere and is sensitive to SC influence [e.g., *Kodera*, 1995; *Thompson and Wallace*, 1998; *Baldwin and Dunkerton*, 1999; *Ruzmaikin and Feynman*, 2002].

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